PENNSTATE ARL

iMAST

Institute for Manufacturing and Sustainment Technologies

QUARTERLY 1998 No.4

Maritime Prepositioning Ships (MPS), USNS fast sealift ships, and U.S. Navy warships like those pictured above will benefit from the efforts of the joint MARITECH/Navy ManTech Program.

iMAST Hosts MARITECH/Navy ManTech Joint Meeting

The MARITECH Advanced Shipbuilding Enterprise (ASE) and U.S. Navy ManTech Program Centers of Excellence (COEs) recently held a joint meeting at The Pennsylvania State University's Applied Research Laboratory. The event was hosted by the Institute for Manufacturing and Sustainment Technologies (iMAST). The purpose of the meeting was to establish a joint understanding of the efforts of the two groups and identify those areas where Navy ManTech COEs and MARITECH ASE efforts can be mutually leveraged to maximize the benefits for improved competitiveness to the U.S. shipbuilding industry.

The MARITECH ASE program is an outgrowth of the Defense Advanced Research Project Agency (DARPA)-managed MARITECH program which was initiated in 1993 and concluded during fiscal year 1998. The DARPA program has been a major force in placing many of our shipbuilders on the road to recovery. The U.S. Navy, working with industry, DARPA, the Maritime Administration, and the U.S. Coast Guard worked to develop the post-MARITECH program.

The mission of MARITECH ASE is to manage and focus national shipbuilding research and development funding on technologies that will reduce cost of warships for the U.S. Navy and will establish U.S. international shipbuilding competitiveness. To this end, an investment of an estimated $400 million is planned over a five year period starting in Fiscal Year 1999. The six major initiatives for this planned investment are:

- Shipyard production process technologies
- Business process technologies
- Product design and material technologies
- Systems technologies
- Facilities and tooling
- Crosscut initiatives

Each major initiative will consist of four to nine sub-initiatives.

During the two day meeting at ARL Penn State, the eight U.S. Navy ManTech Centers of Excellence made presentations on their capabilities and technical expertise to an audience consisting of shipyard, industry, Penn State faculty and staff, and the U.S. Navy. In summary presentations, each Center of Excellence identified how they could support each of the major initiatives. The result was a strong showing in all of the initiative areas. U.S. Navy ManTech COEs will provide a vital resource to help shipyards produce more affordable Navy ships for the future. For more information about this program, please contact Mr. Robert Johnson (ARL Penn State) at (814) 863-7140 / e-mail: raj1@psu.edu or Mr. Leo Plonsky (ONR MARITECH Program Officer) at (215) 697-9528 / e-mail: plonskl@onr.navy.mil

FOCUS ON REPAIR TECHNOLOGY

A U.S. Navy Manufacturing Technology Center of Excellence

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1998**	2. REPORT TYPE	3. DATES COVERED **00-00-1998 to 00-00-1998**
4. TITLE AND SUBTITLE **iMAST Quarterly, 1998 Number 4**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Penn State University,Applied Research Laboratory,Institute for Manufacturing and Sustainment Technologies,State College,PA,16804**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

PENNSTATE

iMAST

Applied Research Laboratory
Institute for Manufacturing and Sustainment Technologies

DIRECTOR
Henry E. Watson
(814) 865-6345 hew2@psu.edu

THRUST LEADER
Mechanical Drive Transmission Technologies
Suren B. Rao, Ph.D.
(814) 865-3537 sbr1@psu.edu

THRUST LEADER
Materials Science Technologies
Maurice F. Amateau, Ph.D.
(814) 863-4481 mfa1@psu.edu

THRUST LEADER
High-Energy Processing Technologies
J. Thomas Schriempf, Ph.D.
(814) 863-9912 jts6@psu.edu

THRUST LEADER
Navy/Marine Corps Repair Technologies
Lewis C. Watt
(814) 863-3880
lcw2@psu.edu

iMAST ADMINISTRATOR and EDITOR
Gregory J. Johnson
(814) 865-8207 gjj1@psu.edu

STAFF ASSISTANT
Carol Ott
(814) 863-3207 (814) 863-1183 FAX
cvo1@psu.edu

WORLD WIDE WEB
www.arl.psu.edu/core/imast/imast.html

NAVY PROGRAM MANAGER
Ted Hicks
(215) 697-9528 hickst@onr.navy.mil

©1998. The iMAST quarterly newsletter is published by the Manufacturing Science and Advanced Materials Processing Institute of the Applied Research Laboratory at Penn State, University Park, Pa. iMAST is a nonprofit organization sponsored by the U.S. Navy Manufacturing Technology (MANTECH) Program, Office of Naval Research, under Navy Contract N00039-97-0042. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the U.S. Navy. Send mail list requests or address corrections to: iMAST Administrator, ARL Penn State, P.O. Box 30, State College, PA 16804-0030 or e-mail: cvo1@psu.edu
Parcel delivery address (UPS, FedEx, USPS): N. Atherton St. Rear; Research Building West, State College, PA 16804.
Penn State is an equal opportunity/affirmative action university.
U.Ed. ARL 99-6

IN THIS QUARTERLY

DIRECTOR'S CORNER

New Name for the New Year

You may have noticed we have changed our name. The Office of Naval Research requested that we change our name to better reflect our scope and mission. While our

initial focus has and continues to be materials and manufacturing, our faculty and staff have been increasingly tasked to address repair and sustainment issues relative to Navy and Marine Corps combat systems. We have previously been identified as the coordinator for Navy and Marine Corps repair technology issues, but that was not reflected in our name. It is a coincidence that our name change coincides with this particular newsletter issue. We had previously planned that our focus for this 4th quarterly newsletter would be on repair technology. I am delighted, therefore, to introduce you, in this issue, to Ben Bard, one of our best and brightest researchers who is specifically addressing a repair-related issue.

With the Department of the Navy acquiring fewer combat systems at ever-increasing cost, we need to ensure that these systems last well into the next century. Repair technology will play an increasingly important role in that part of the sustainment and readiness equation. The Department of Defense (DoD) currently spends more money on equipment maintenance each year than the entire annual budget of NASA. While the money allocated for this maintenance is significant, it is also for very demanding and difficult work. The majority of the maintenance work noted is currently conducted at naval shipyards and depots. The ultimate customer is that forward deployed sailor and marine serving with the fleet.

Repair efforts at the depots and shipyards are extensive. This includes not only major repairs, but overhaul and many other diverse and complex industrial processes. In an effort to make the depot and shipyard maintenance organizations more effective, the Department of Defense has been looking at additional approaches for doing business. One suggestion has been to look into partnering with industry. While partnering remains an issue before (and between) Congress and the DoD, it is interesting to note that repair facilities are not sitting idle or doing business as usual. The Naval Aviation Depot at North Island, for example, recently won the Council for Quality and Service's best-in-class productivity award as the only government entity competing against the private sector. It was the first time a government organization of its nature won against large private firms in this three year old competition. Depot and shipyard commanders know that they must operate like a private business in order to satisfy their customers and remain viable. And it appears they are doing a good job of it. The Navy's repair technology program will assist these commanders in reducing the risks associated with changes to schedules, cost, and performance enhancement. The repair technology investment will bridge the gap between the capability of the repair process and the sustainment needs of the weapon system.

Henry Watson

PENNSTATE iMAST

MECHANICAL DRIVE TRANSMISSION TECHNOLOGIES
MATERIALS SCIENCE TECHNOLOGIES
HIGH-ENERGY PROCESSING TECHNOLOGIES
NAVY/MARINE CORPS REPAIR TECHNOLOGIES

Focus on Repair Technology

Full-Field NDI with Phase-Stepping Digital Shearography

by Benjamin A. Bard

The increasing popularity of complex composite materials for aerospace structures has brought with it the necessity for more advanced nondestructive inspection (NDI) capabilities. Rock or bird strikes on composite wings, accidental tool drops, interlayer voids left during the manufacturing process, and skin-to-core disbonds in honeycomb structures are only a few of the commonly found flaws.

An NDI measurement tool must possess several characteristics in order to be successful in flaw detection. A good measurement threshold is desirable so that subtle anomalies can be detected. Measurement resolution must be such that a subtle local anomaly will be noticed relative to its "normal" surroundings. Dynamic range is important since, in a single measurement, severe perturbations may occur in the neighborhood of slight ones, and it is desirable to avoid having one conceal the other. High spatial resolution can be useful not only to more closely determine the spatial extent (size) of a flaw, but to locate small flaws. A high signal-to-noise ratio (SNR) is critical, aiding in many of the above requirements, as well as in the visual aspect of the displayed results; for the most part, human operators pick out flaws visually, high contrast being critical to this process. Other issues pertain only to practicality and convenience. The ultimate system should be able to work on metal and nonmetal surfaces, rough or smooth, flat or curved. Tear-down of the structure is undesirable, so the system should be lightweight and portable. If it is to be used in non-laboratory environments, it must be sufficiently invulnerable to disturbances such as thermal drifts, ambient light, and stray vibrations. Finally, speed and convenience are not only kind, but reduce operator fatigue.

Existing measurement tools include, for example, ultrasonics (portable and C-scans), eddy current, x-ray, dye penetrant, moiré interferometry, holographic interferometry, and the ubiquitous coin tap. Each of these NDI tools has strengths and weaknesses. For instance, ultrasonics has high sensitivity, but normally requires time-consuming scanning to achieve high spatial resolution. Eddy current testing is a useful technique but only if the structure under investigation is conductive. Holographic interferometry has incredibly high sensitivity and does not require scanning, but is somewhat limited to laboratory settings due to its environmental vulnerability.

Electronic shearography is a full-field, noncontact, optical, speckle interferometric technique. Many examples in the literature cite its use in the field of NDI.[1–4] Shearography has found its way into the NDI spotlight due to its combination of a full-field, noncontact nature with high sensitivity and environmental stability. The ARL Electro-Optics Group, under the auspices of the REPTECH program, has developed a portable shearography system with enhanced flaw detection capabilities relative to commercially available shearography systems. These enhancements will be discussed in later sections.

Background

Speckle-shearing interferometry, more commonly known as shearography, is an offspring of holographic interferometry and was first introduced by Hung and Taylor[5] and Leendertz and Butters[6] over 20 years ago. Like its holographic cousin, it has evolved over the years from a film-based to video-based system, and finally to its current computer-based digital form.

A basic digital shearography system is shown in Figure 1. Coherent laser light is expanded to illuminate the entire object under investigation, and imaged by a CCD camera. Since the surface structure is rough with respect to an optical wavelength, diffusive reflection occurs and the image captured by the CCD camera is that of a speckle pattern. The key to shearography is the shearing element placed in front of the CCD lens. This element can be a glass wedge of small angle, a birefringent wedge, or a lateral Michelson interferometer, among others.[e.g., 7–9] (The current work uses a Michelson interferometer.) The purpose of the shearing element is to split, or "shear," the wavefront reflected from the object into two wavefronts which then interfere with each other. It is this "self interference" that gives shearography its robustness, allowing it to leave the confines of the laboratory.

PROFILE

Benjamin A. Bard is a research associate and head of the Manufacturing Technology Electro-Optics Group. A native of Minneapolis, Minnesota, Dr. Bard received his B.A. in physics from Hamline University in St. Paul, Minnesota, and his Ph.D. in acoustics from Penn State University where he was the recipient of the Penn State College of Engineering Dean's Fellowship.

Dr. Bard's doctoral work involved the combination of phase-stepping shearography with laser strobing for full-field, noncontact, *quantitative* analysis of structural vibrations. In the process of this work, he also co-developed a novel approach for visualizing ultrasonic wave fields on the surface of elastic solids using shearography.

Dr. Bard's research interests include optical methods of vibration analysis, NDI techniques utilizing optics and vibration, structural acoustics and guided wave propagation, and acoustics visualization. He is a member of SPIE and the Acoustical Society of America, and participates in the ASA Structural Acoustics and Vibration Technical Committee. Dr. Bard can be reached at (814) 865-1870, or by e-mail at bab132@psu.edu

CONTINUED FROM PAGE 3

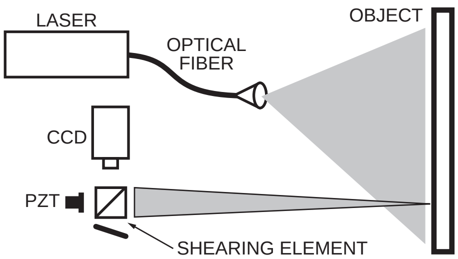


Figure 1. Basic schematic of phase-stepping shearography system.

Multiple Exposures and Differential Displacement

Shearography is a comparative technique. This means that it examines the difference between two slightly different surface positions. This difference comes about from some sort of excitation, either static (e.g., thermal or vacuum loading) or dynamic (e.g., vibration). Speckle patterns (images of the object illuminated by laser light) representing the object's position are hence captured before and after deformation, and compared to see the change.

This change measured by shearography is not simply the displacement caused by the deformation. Due to the shearing element, the measured quantity is *differential displacement*, the relative displacement between two points on the object separated by the optical shearing distance. Figure 2 shows a surface before and after deformation, a pair of object points that are optically sheared together, and the resulting differential displacement.

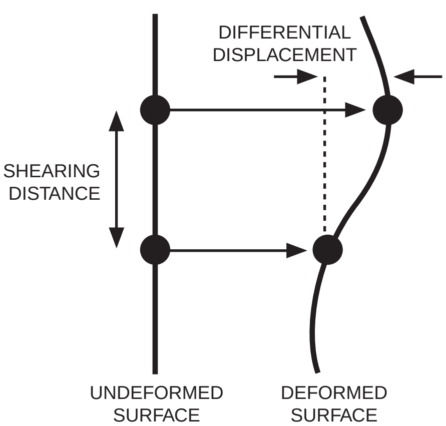


Figure 2. Differential displacement of deforming surface.

A shearography measurement has several advantages over a similar holography (displacement) measurement. First of all, unwanted rigid-body translations (out-of-plane), within reason, do not affect differential displacement. Second, laser coherence requirements are relaxed since the optical path length difference is greatly reduced. Third, as the shearing distance decreases, differential displacement begins to approximate a displacement derivative, directly proportional to some elements of the strain tensor. Since subsurface flaws often induce strain concentrations on the object's surface, shearography has naturally high flaw detection capability. Fourth, adjusting the shearing distance effectively adjusts the sensitivity of the measurement. Finally, an advantage of being a speckle technique, curved surfaces and optically rough surfaces are easily measured.

Fringes and Phase-Stepping

Images are captured before and after deformation and somehow compared to indicate the change. The traditional (and most common commercial) method for this comparison is the formation of speckle correlation fringes by subtraction. This method simply subtracts one image from the other, pixel by pixel, and rectifies the difference. The two images and their difference are expressed mathematically by (Eq. 1)

$$I_1 = I' + I'' \cos(\phi),$$
$$I_2 = I' + I'' \cos(\phi + \Delta),$$
$$I_{sub} = \left| 2I'' \sin\left(\phi + \frac{\Delta}{2}\right) \sin\left(\frac{\Delta}{2}\right) \right|.$$

Here, I' is the *bias intensity*, I'' the *modulation intensity*, ϕ a random phase variable due to the diffuse reflection of laser light from the surface, and Δ a quantity directly proportional to the differential displacement due to deformation. (Note that all quantities are functions of (x,y), where this notation has been suppressed.) I_{sub} describes a pattern of speckle correlation fringes: a high-spatial-frequency carrier term, $\sin(\phi+\Delta/2)$, amplitude modulated by a low-frequency term, *sin*($\Delta/2$). The carrier is nullified when *sin*($\Delta/2$) = 0, or $\Delta = 2n\pi$. This leads to a dark fringe each time $n = 0, 1, 2, 3, \ldots$.

The fact that ϕ exists in the resulting fringe pattern adds high noise content to the final fringe pattern. The resulting low SNR allows deformation information (i.e., Δ) to be determined only at limited locations, the fringe centers. While difficult, each fringe could receive a deformation value once its center is located, and interpolation used to create a continuous profile. Although not directly shown by Eq. 1, each fringe represents a $\lambda/2$ differential displacement of the surface at that location, where λ is the wavelength of the laser light.

Phase stepping is another method for measuring the same deformation. In this technique, a series of images, rather than a single image, is captured at each object position. Between each of the images, an optical phase shift is introduced between the two interfering wavefronts. This can be accomplished in shearography in several ways, including lateral translation of a shearing wedge,[10] the use of a liquid crystal or electro-optic modulator,[11] or the shifting of a mirror within a Michelson interferometer via a PZT disk.[8]

For the present discussion, a four-step algorithm will be used. With this algorithm, four phase-stepped images are captured before deformation, and four more after deformation. The images are expressed mathematically by (Eq. 2)

$$I_1(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y)],$$
$$I_2(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y) + \pi/2],$$
$$I_3(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y) + \pi],$$
$$I_4(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y) + 3\pi/2],$$
$$I_5(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y) + \Delta(x,y)],$$
$$I_6(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y) + \Delta(x,y) + \pi/2],$$
$$I_7(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y) + \Delta(x,y) + \pi],$$
$$I_8(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y) + \Delta(x,y) + 3\pi/2].$$

These equations represent a fully determined system, allowing direct calculation of $\Delta(x,y)$ at each pixel by (Eq. 3)

$$\Delta(x,y) = \tan^{-1}\left[\frac{I_8(x,y) - I_6(x,y)}{I_5(x,y) - I_7(x,y)}\right] - \tan^{-1}\left[\frac{I_4(x,y) - I_2(x,y)}{I_1(x,y) - I_3(x,y)}\right].$$

It is immediately seen that the random phase variable ϕ has now been completely removed from the calculated data, leaving only the desired quantity at each pixel. The SNR is enhanced considerably by this fact, as seen in Figure 3 which compares a fringe pattern and phase map for the identical deformation. Now there are no fringes

giving hints of $\Delta(x,y)$ at select locations; rather, the deformation $\Delta(x,y)$ is calculated independently at every single pixel. The wealth of data acquired is now based upon the number of pixels mapped to the object's surface, not the number of fringes appearing due to the specific deformation. At each pixel, the measurement resolution is based primarily on the bit depth of the acquired images, and the measurement threshold is based on system noise concerns, increased from $\lambda/2$ to $\lambda/100$ or even $\lambda/1000$ in laboratory settings.

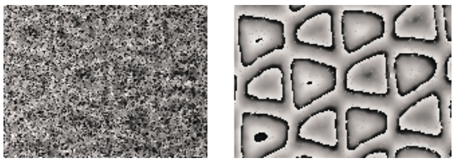


Figure 3. (left) subtraction fringes, and (right) phase map for identical deformation of honeycomb.

One key aspect of the calculated phase map is its "wrapped" nature. Eq. 3 shows that $\Delta(x,y)$ is calculated via a $\tan^{-1}$ function which returns only the principal value of the calculated angle, the value modulo 2π. Each sudden dark-to-light transition, although representing a continuous deformation, jumps from $-\pi$ to $+\pi$ suddenly. These phase jumps can, if desired, be removed by a phase unwrapping algorithm.

Portable Real-time Phase-stepping Shearography System

Due to the amount of data contained in eight images and the calculation time to realize Eq. 3, phase calculation has traditionally been a post-processing step. Real-time feedback to the user has long been possible only with subtraction fringes which can occur at video frame rates. The system developed at ARL Penn State improved upon the existing technology in several ways. A high resolution digital CCD camera was used to resolve smaller flaws. The PZT phase stepping method was used in order to take advantage of the potential phase-stepping speed. A computer with a fast CPU was used along with control code that tightly integrated phase stepping, data acquisition, phase calculation, and phase map display. The final system is capable of capturing eight images, calculating phase, and displaying the phase map on screen every one to two seconds.[12] This combined the substantial benefits of phase stepping with the real-time feedback of commercial subtraction units.

Along with our technology transfer partner, Laser Technology, Inc. (LTI), a portable phase-stepping shearography head was developed. This unit combined the optics and control code developed at Penn State with a portable vacuum head manufactured by LTI. The purpose of the vacuum is twofold: to attach the unit firmly to the part being examined, and to supply incremental vacuum excitation to deform the object during measurement. When thermal excitation is desired, the vacuum level is not altered during testing.

This prototype unit was successfully demonstrated at the North Island Naval Air Station in October 1997. A picture of the portable head being used for inspection of an A/V-8B Harrier (at the Cherry Point NADep) is shown in Figure 4.

Figure 4. Portable shearography head (includes optical system and vacuum excitation).

Flaw Detection With Digital Shearography

The basic premise for flaw detection with shearography is that when the entire surface is subjected to a load, the surface area just above a flawed region will deform differently than the surrounding surface area, evidence of the presence of the flaw. The choice of excitation remains somewhat of a black art, but certainly depends on material properties as well as the type, location, and severity of the flaw being investigated.

Figure 5 shows a shearography phase map of an aluminum/aluminum honeycomb. The image represents approximately one square foot of the honeycomb panel while it was undergoing thermal expansion. Due to optical shearing, each "healthy" cell shows up as two side-by-side trapezoids. A large disbonded region is easily seen, where the skin above many cells has expanded without constraint. This measurement took only a couple of seconds to make, and was completely noncontact.

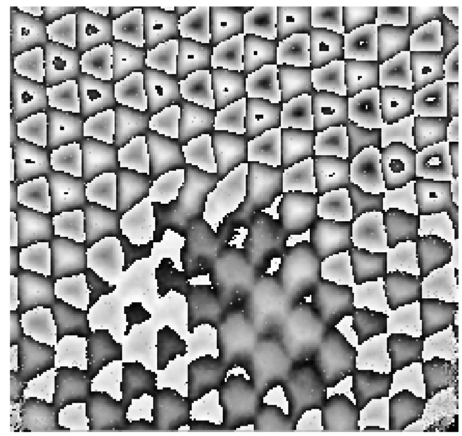


Figure 5. Phase map of aluminum/aluminum honeycomb under thermal expansion.

Another NDI example can be seen in Figure 6, a phase map of a CH-53 rotor blade. This test, utilizing the vacuum excitation of the portable shearography head, examined the region where aluminum fairing and spar were assumed to be bonded. In this case, the good bond line is clearly seen; beneath the bond line is expected deformation of the unsupported skin.

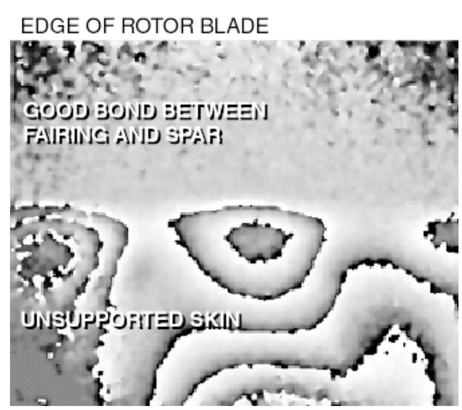


Figure 6. Phase map of CH-53 rotor blade bond line (vacuum excitation).

CONTINUED FROM PAGE 5

A final NDI example is shown in Figures 7a and 7b. Figure 7a shows the phase map of an F/A-18 aileron with composite skin and foam core under a vacuum load. Five delaminations due to impact damage can be seen. The four large arcing stripes are phase jumps due to the calculation of phase modulo 2pi. A two-dimensional phase unwrapping algorithm capable of coping with speckle noise was developed to reconstruct the continuous phase, removing these jumps. After unwrapping and gradient filtering, Figure 7a is transformed into Figure 7b, confidently displaying the five delaminations with no background fringes.

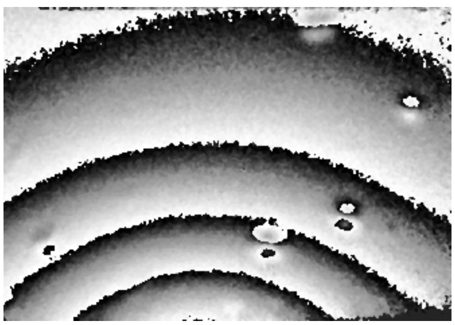


Figure 7a. Impact damage on an F/A-18 aileron (wrapped phase map).

Figure 7b. Impact damage on an F/A-18 aileron (unwrapped phase map and filtered).

Conclusions

Current commercial shearography systems employ subtraction fringes to convey deformation information. In this form, shearography is a portable, full-field (non-scanning), noncontact, robust form of interferometry which provides moderate spatial resolution and real-time feedback to the user. With the addition of fast phase stepping to the portable system, the SNR is increased dramatically, along with the flaw detection sensitivity. Careful design of the electro-optical system allows near real-time feedback of phase maps to the user. The use of a high-resolution digital camera provides the ability to detect smaller flaws. Post processing steps such as phase unwrapping, available only to phase maps and not to fringe patterns, can provide further insight into the data.

The prototype portable system has proven successful on a variety of materials including metal and composite honeycombs and composite panels. The combination of vacuum and thermal excitation is effective on most parts. Future research into ultrasonic excitation for deeper and more subtle flaws is currently underway.

Acknowledgments

This project was completed in cooperation with Guowen Lu and Shudong Wu of the ARL Electro-Optics Group, as well as with assistance from Laser Technologies, Inc. The author is grateful for support from the Institute for Manufacturing and Sustainment Technologies at The Pennsylvania State University's Applied Research Laboratory. The Institute is a nonprofit organization sponsored by the United States Navy Manufacturing Technology (ManTech) Program, Office of Naval Research (contract number N00039-97-0042). Any opinions, findings, conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the U.S. Navy.

References

[1] Y.Y. Hung, "Shearography for non-destructive evaluation of composite structures," *Opt. Lasers Eng.* 24, pp. 161–182, 1996.

[2] J.W. Newman, "Shearographic inspection of aircraft structure," *Mater. Eval.* 49, pp. 1106–1109, 1991.

[3] T.C. Chatters and S. Krishnaswamy, "Nondestructive evaluation using shearing interferometry," in *Rev. Prog. Quant. NDE*, edited by D.O. Thompson and D.E. Chimenti (Plenum Press, New York, 1992), Vol. 11, pp. 479–486.

[4] S.L. Toh, H.M. Shang, F.S. Chau, and C.J. Tay, "Flaw detection in composites using time-average shearography," *Opt. Laser Technol.* 23, pp. 25–30, 1991.

[5] Y.Y. Hung and C.E. Taylor, "Measurement of slopes of structural deflections by speckle-shearing interferometry," *Exp. Mech.* 14, pp. 281–285, 1974.

[6] J.A. Leendertz and J.N. Butters, "An image-shearing speckle-pattern interferometer for measuring bending moments," *J. Phys. E.: Sci. Instrum.* 6, pp. 1107–1110, 1973.

[7] Y.Y. Hung, "Shearography: A new optical method for strain measurement and nondestructive testing," *Opt. Eng.*, 21(3), pp. 391–395, 1982.

[8] W.J. Bisle, D. Scherling, and G. Tober, "Phase stepping shearography for testing commercial aircraft structures; an application review of advanced image processing techniques for shearography," in *Rev. Prog. Quant. NDE*, edited by D.O. Thompson and D.E. Chimenti (Plenum Press, New York, 1996), Vol. 15.

[9] B.A. Bard, G.A. Gordon, and S. Wu, "Laser-modulated phase-stepping digital shearography for quantitative full-field imaging of ultrasonic waves," submitted for publication to *J. Acoust. Soc. Am.*

[10] M. Owner-Petersen, "Digital speckle pattern shearing interferometry: limitations and prospects," *Appl. Opt.*, 30(19), pp. 2730–38, '91.

[11] B.A. Bard, S. Wu, and B.R. Tittmann, "A compact digital phase-stepping shearography system," in *Rev. Prog. Quant. NDE*, edited by D.O. Thompson and D.E. Chimenti (Plenum Press, New York, 1996), Vol. 15, pp. 673–677.

[12] G. Lu, B.A. Bard, and S. Wu, "A Real-time Portable Phase-stepping Shearography System for NDE," Proc. Soc. Photo-Opt. Instrum. Eng., 3397-25, 1998.

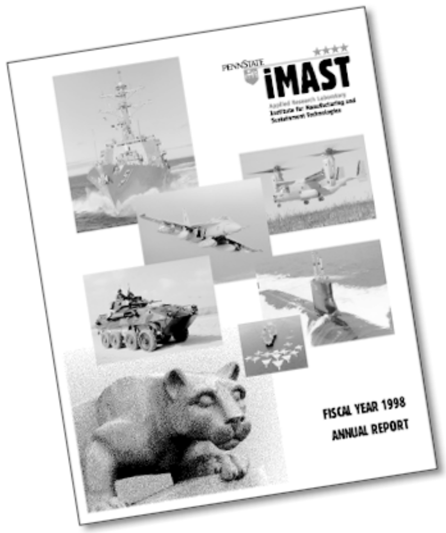
INSTITUTE NOTES

FY-99 ManTech New Start Project Prioritizations

The Office of Naval Research recently announced ManTech and REPTECH project prioritizations eligible to begin in fiscal year 1999 upon final approval from ONR program officers. The following projects were identified for iMAST:

Arresting Gear Poured Sockets (NAVAIR).
This project will address the manufacturing procedure for zinc poured sockets used to terminate the ends of the wire rope used to arrest aircraft aboard aircraft carriers. The current method is extremely process-dependant. For more information about this project, please contact Dr. Maurice Amateau at (814) 865-0250 or by e-mail at: mfa1@psu.edu

AAV Enhanced Applique Armor Kit Product Improvement (MARCORSYSCOM).
This project will address ballistic deterioration issues related to layer corrosion and delamination. For more information about this project, please contact Dr. Maurice Amateau at (814) 865-0250 or by e-mail at: mfa1@psu.edu



Laser Cutting and Welding of Structural Shapes (NAVSEA).
This project will address combatant ship structural shape issues relative to adequate stiffening plates to resist loading under routine service and combat conditions. For more information about this project, please contact Dr. Thomas Schriempf at (814) 863-9912 or by e-mail at: jts6@psu.edu

Cold Gas Dynamic Spray Wear-Resistant Coatings for Aircraft Carrier Steam Catapult Pistons (NAVAIR).
This project will address reduced service life in subject pistons aboard aircraft carriers. For more information about this project, please contact Dr. Maurice Amateau at (814) 865-0250 or by e-mail at: mfa1@psu.edu.

Overspray Reduction and Collection Techniques for Automatic Spray Painting of U.S. Navy Ships (NAVSEA-REPTECH).
This project will address current methods used for ship hull coating that results in low transfer efficiency, nonuniform coating thickness, and emission of volatile organic compounds and hazardous air pollutants. For more information about this project, please contact Mr. Lewis Watt at (814) 863-3880 or by e-mail at: lcw2@psu.edu

Heavy Equipment Repair Improvement (MARCORSYSCOM-REPTECH).
This project will address expensive deterioration-related issues relative to aging heavy duty combat service support equipment. For more information about this project, please contact Dr. Mark Traband at (814) 865-3608 or by e-mail at: mtt1@psu.edu

Refined Mobile Manipulator for Flashlamp Carbon Dioxide Stripping Process (NAVAIR-REPTECH).
This project will address paint removal and hazardous waste stream by-products associated with the removal of paint from large aircraft such as the C-130 and P-3. For more information about this project, please contact Mr. William Sabol at (814) 863-3880 or by e-mail at: wjs4@psu.edu

LAV Crew Compartment Heater (MARCORSYSCOM-REPTECH).
This project will address water and debris entry into the LAV crew compartment heater unit via the exhaust port causing corrosion and failure of the combustion exhaust system. For more information on this project, please contact Mr. Dennis Wess at (814) 865-7063 or by e-mail at: dbw105@psu.edu

iMAST Annual Report

A limited number of copies of our fiscal year 1998 annual reports are now available by contacting the iMAST administrator at (814) 865-8207. The document is also live on-line or you may download a printable .pdf version. Our web address is: www.arl.psu.edu/core/imast/imast.html

BGen James M. Feigley, USMC, Commanding General, Marine Corps Systems Command, accepts a plaque commemorating lead systems command designation from Mr. Henry Watson, director of ARL Penn State's iMAST program. Joining the general are Mr. Larry Kreitzer, executive director, MARCORSYSCOM (far left) and Ms. Amy Rideout, MARCORSYSCOM ManTech coordinator (far right).

MARCORSYSCOM Designated iMAST Lead Systems Command

The Marine Corps Systems Command was recently designated iMAST's lead systems command by the Chief of Naval Research, Rear Admiral Paul Gaffney. The designation means MARCORSYSCOM will administratively monitor and coordinate the efforts of the institute in concert with the Navy's ManTech Program.

Danzig New SecNav

The Honorable Richard Danzig was recently sworn in as the 71st Secretary of the United States Navy. Mr. Danzig previously served as an Under Secretary of the Navy. During 1995, Mr. Danzig was the featured and honored guest speaker at ARL's 50th anniversary celebration at The Pennsylvania State University.

Institute administrator Greg Johnson is shown here briefing Mr. Danzig (then Under Secretary of the Navy) on an iMAST project during a 1995 visit to ARL Penn State. Also looking on is former Chief of Naval Research, RADM Marc Pelaez.

iMAST Participates in DMC '98

Members of iMAST recently participated in the annual Defense Manufacturing Conference, which was held in New Orleans, Louisiana. Once again, leaders from government, industry, and academia assembled to exchange perspectives and information relative to manufacturing technology and industrial modernization. This year's theme, "ManTech for Affordable Readiness and Modernization" set the forum for a discussion concerning insight into the future of defense manufacturing and sustainment for both military and commercial products.

Drs. Al Segall and Suren Rao of iMAST both presented papers at the conference. Next year's annual conference is scheduled to be held in Miami, Florida from 29 November through 2 December 1999.

CALENDAR OF EVENTS

31 Jan–2 Feb	NDIA Tactical Vehicle Wheel Conference	Monterey, CA
28 Feb–4 Mar	The Minerals Metals and Materials Society Annual Meeting	San Diego, CA
22 Mar	SME Powder Metallurgy Clinic	Los Angeles, CA
23 Mar	SME Metal Injection Molding Clinic	Los Angeles, CA
24 Mar	SME P/M Heat Treating and Sintering Clinic	Los Angeles, CA
25–26 Mar	DoD ’99 10th Annual U.S. Defense Budget Conference	Arlington, VA
29 Mar–1 Apr	10th U.S. Army Ground Vehicle Survivability Symposium	Monterey, CA
30–31 Mar	Navy League Sea–Air–Land Expo	Washington D.C.
6-8 Apr	AW&ST Maintenance, Repair, and Overhaul ’99 Conference	Atlanta, GA
19 Apr	SME Fundamentals of Induction Heating Clinic	Nashville, TN
19–22 Apr	53rd Society for Machining Failure Prevention Technology	Virginia Beach, VA
20–21 Apr	NCEMT Manufacturing Technology for Aerospace Materials	Crystal City, VA
20–21 Apr	SME Induction Heating Technology and Applications Clinic	Nashville, TN
May (TBA)	ARL Materials and Manufacturing Advisory Board Meeting	State College, PA
3–5 May	AIAA Global Air & Space ’99 Expo	Washington, D.C.
3–6 May	2nd NDIA Joint Classified Ballistics Symposium	Monterey, CA
23–26 May	13th Annual NCMS Technical Conference and Expo	Orlando, FL
25–27 May	AHS Forum 55	Montreal, Canada
13–17 Jun	NDIA 5th Annual Joint Aerospace Weapons Support Expo	San Diego, CA
13–15 Sep	4th Annual Conference of Spray Forming	Baltimore, MD
20–23 Sep	Marine Corps League Modern Day Marine Expo	Quantico, VA
21–22 Sep	NCEMT Modern Shipbuilding Technologies	Crystal City, VA
24–27 Oct	AGMA Expo	Nashville, TN
Nov (TBA)	ARL Materials and Manufacturing Advisory Board Meeting	State College, PA
29 Nov–2 Dec	Defense Manufacturing Conference ’99	Miami, FL

“The Navy and the defense industry have to be better, quicker, and cheaper. It is a necessity, not an option. We have to examine and question everything we do and see if there is a better way to accomplish tasks. This requires new ideas.”

—Admiral Paul Reason, Commander-in-Chief, U.S. Atlantic Fleet, 1998

PENNSTATE
1855
Applied Research Laboratory
P.O. Box 30
State College, PA 16804–0030

ADDRESS CORRECTION REQUESTED